SINGLE CHANNEL WIDEBAND PULSE TIME MODULATION

BY
D. S. HOPKINS

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WIDEBAND PULSE TIME MODULATION

by

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Submitted in partial fulfillment
of the requirements
for the
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PREFACE

This paper is concerned with the preliminary design and construction of a single-channel wideband pulse time modulation system. In so far as this writer is able to determine, no other work has been done on the subject of wideband PTM.

A single channel of the normal PTM multiplex systems usually covers a bandwidth of 0.3 to 3.0 KC and the multiplexing is done by time division. A single-channel wideband PTM, capable of covering 0.3 to 60 KC, would be of tremendous advantage to the present older types of frequency division multiplex systems. If a suitable method of converting a complex wideband signal to some form of pulse modulation is available, then the existing communication systems can take advantage of the microwave region for transmission. The equipment described is a first attempt in that direction.

This work was accomplished during a three months association with the engineers of the Federal Telecommunication Laboratories who have pioneered in all types of pulse communication systems. The writer wishes to express his appreciation to Messrs. A. M. Levine, B. B. Lair and R. R. Waer of FTR who were very generous in sharing their ideas and knowledge.

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CHAPTER I

INTRODUCTION

1.1 History

In the earliest days of electrical communications, transmission of intelligence was by means of short bursts, or pulses, of energy. This is exemplified by the dots and dashes of the Morse code. Development of continuous wave and modulated continuous wave equipment soon overshadowed this first method of communication and improvement of pulse transmissions was practically neglected.

It was not until the late thirties that radar and commercial television gave the field of pulse techniques new impetus. Then World War II brought the classification of secret and little or no information wasavailable until 1945. Since that time numerous articles have appeared in the literature showing the employment of pulse transmission in television, fascimile, multiplex communications systems, high speed electronic switching and many other fields.

The history of pulse modulation, as applied to the transmission of speech and music actually dates back to the nineteen-twenties and nineteen-thirties. In 1924, R. A. Heising applied for and was granted a patent under the title "Transmission System", and which described a method similar to modern pulse-width modulation.[1] Other American patents, as well as a series of British patents, describing pulse modulation and various methods for

1. See page 5.

producing it appeared during the period between nineteen thirty-four and nineteen forty-one. Pulse modulation was applied to a few experimental equipments during this period, but the use and development of the various forms of pulse modulation did not begin until after the beginning of World War II. As mentioned previously, this work was kept secret during the war because of the military application of radar and the advantages that this type of modulation seemed to offer for military multiplex communication systems.

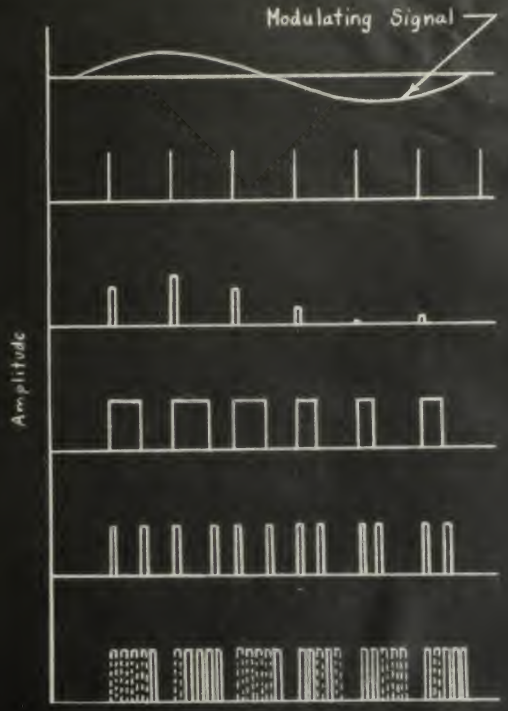
Since 1945 pulse modulation has had considerable employment in military and commercial multiplex equipment. The most extensive to date was developed by the Federal Telecommunication Laboratories and contains ninety-six channels on a single carrier.

At the present time two basic methods of pulse modulation are in general use; pulse-time modulation, PTM, and pulse-code modulation, PCM. The first of these, PTM, has been under development for the greatest length of time and consequently has taken its place alongside the older types of modulation. It is in commercial use to a considerable extent, mostly in the form of time division multiplex radio links. An ambitious development program for PCM is now in progress and promises eventually to overshadow the advantages of PTM

1.2 Basic Types of Pulse Modulation

Figure 1. illustrates the four basic types of pulse modulation now recognized. Variations in method of modulation gives rise to slightly different nomenclature, but all forms of pulse modulation now in use, or being developed, fall into one of these catagories. Notice that all four methods of transmission have the common denominator of a periodic sampling of the signal. The principal difference is the means by which the amplitude of each signal is transmitted.

The simplest form is pulse-amplitude modulation, PAM. The amplitude of the pulses is directly proportional to the amplitude of the modulating signal at the instant of sampling. In effect we have been using this type of modulation for quite some time. If the intermediate frequency of a superhetrodyne receiver is considered as the sampling frequency, then the output of the diode second detector, prior to filtering, can be thought of as amplitude-modulated pulses. PAM has been used in experimental or laboratory equipments to investigate the theoretical ideas involved in this type of circuitry. Both theory and experimental data show that the sampling rate must be greater than twice the highest modulating frequency for successful demodulation; the signal to noise ratio, while an improvement over that of amplitude and frequency modulation, is not as good as the other forms of pulse modulation.



Basic Types of Pulse Modulation

Figure 1

Pulse-width modulation[1], PWM, was one solution to the problem of improving the signal to noise ratio. This method is similar to PAM in that a variation of average power proportional to the instantaneous modulating signal amplitude is obtained. However, constant amplitude pulses of variable width are generated rather than ones with constant width and variable amplitude. The signal to noise ratio is improved principally because this type of pulse transmission permits the use of clippers and limiters in the receiving terminal equipment as illustrated in figure 2.

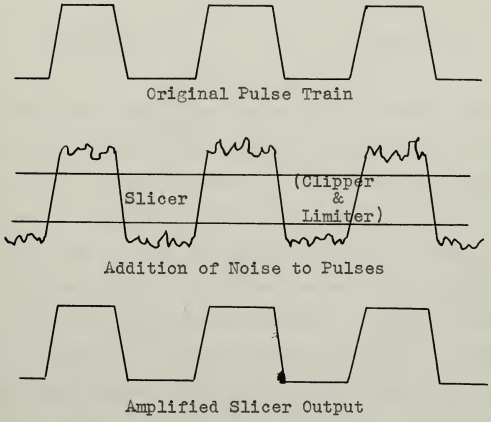
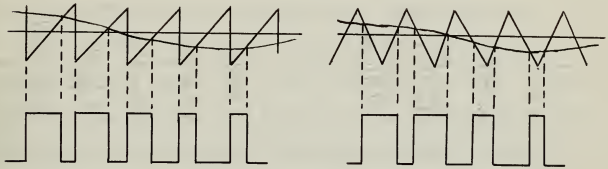


Figure 2.

There are two basic methods of generating PWM which give rise to the slightly different nomenclature used in the literature. The modulation process, which usually consists of slicing a high-frequency saw-tooth voltage at a variable

1. Also referred to as pulse-duration modulation, PDM, and pulse-length modulation, PLM.

level determined by the instantaneous signal value, is shown in figure 3. for so-called asymmetrical and "symmetrical" PWM. The latter is enclosed in quotation marks because, although both edges shift, they do not, in general, shift by exactly equal and opposite amounts.



Asymmetrical Symmetrical

Figure 3.

Realizing that it was wasteful to transmit relatively long pulses when only the timing of the edges carry information, the logical extension of this modulating technique resulted in pulse-time modulation, PTM[1]. The main body of the pulse was omitted and pulses of constant amplitude and duration were used to mark these edges. This resulted in the same noise reduction advantages of PWM, but greater power economy was obtained through lowering the average power requirements needed for the same peak power transmitted.

These new pulses used to mark only the edges of the PWM may have the minimum duration possible for the available bandwidth. This means that they can consist merely

1. Also referred to as pulse-position modulation, or pulse-phase modulation, PPM.

of a rise and decay without any appreciable flat portion or body intervening. At the receiver terminal equipment the area between the two pulses marking the edges of the original width-modulated pulse can be "filled in" to reproduce the original pulse so that the overall system differs essentially only in its transmission characteristics.

As in PWM, the method of modulation leads to the terminology of asymmetrical and "symmetrical" PTM. While some systems developed in England during World War II had PTM which was derived from "symmetrical" PWM, the more recent PTM systems use asymmetrical modulation. This means that only one position-modulated pulse per sampling period is generated; the other pulse being fixed in time. It can easily be seen that this is of great advantage in a multiplex radio link. As an example let us take a four channel PTM system. Using "symmetrical" modulation eight separate pulses must be transmitted to convey one bit of information per channel. That is, channel one requires two pulses for amplitude intelligence, channel two requires two pulses, etc. While it is true that asymmetrical modulation could be transmitted in the same manner, notice that none of the pulses in the "symmetrical" case bears any correlation to the other pulses. The asymmetrical method has an unmodulated pulse representing the leading edge of the original PWM. This means that every other pulse in a multiplex system is fixed in time according to

the sampling rate. Therefore, it is possible to transmit only one reference pulse per frame in order to demodulate all channels. This fact enables asymmetrical modulation to incorporate more channels in a given length of time than does the "symmetrical" method.

Pulse-code modulation, PCM[1], is the fourth basic type of approach in this field. This method of transmission was first described by A. H. Reeves in a French patent issued in 1939. It is a form of pulse transmission in which the amplitude of each sample of the modulation signal is approximated by one of a finite number of amplitudes, both at the transmitter and receiver. By approximating, of quantizing, each sample into one of a discrete number of amplitudes or quanta a large signal to noise ratio improvement is obtained. Since only a finite number of levels is involved it is possible to transmit the information by a coded pulse system similar to a standard teletype signal. If, for example, a modulating signal is divided into a total of 31 levels a five unit binary code system may be used for identifying each of the discrete amplitudes. This reduces the system essentially to an "on-off" type of circuit and greatly improves the signal to noise ratios possible.

PCM is the latest development in the technique of pulse modulation and for particular applications appears

1. Also referred to as pulse-count modulation.

to offer tremendous advantages over all other types of modulation. Considerable research and development is being done on the subject and it is anticipated that eventually this system will approximate a theoretically perfect communication system.

1.3 Advantages of Pulse Modulation

The first advantage claimed for pulse modulation in the earliest patents and articles was greater transmitter efficiency. It was also claimed that, when using short pulses, the peak power could be increased, thus allowing the signal to compete more effectively with noise in the receiver; this in turn increases the maximum range of communication when using the same mean transmitted power. This improvement of signal to noise ratio and the general benefits of nonlinearity in the circuitry became the dominating factor in the middle nineteen-thirties.

Wartime use of pulse multiplex systems pointed out another advantage in the size of equipments needed for a specific job. The simplification and economy in terminal design by elimination of the need for complex filter networks used in frequency division multiplex was one large factor in reducing overall system weight. It was also shown that when repeaters for extending the range of transmission are used, the inherent on-off characteristic of pulse modulation allows a simplified repeater system

to be employed.

An inherent disadvantage of PTM is the wide bandwidth necessary for the transmission of short pulses. However, since most of the pulse multiplex systems are being operated in the microwave region, the spectrum needed is a smaller proportionate amount of the carrier than if the transmitting region was in the MHF or VHF ranges. The use of the microwave region brings out another advantage of pulse type systems. It is much easier to pulse modulate a microwave tube than it is to amplitude or frequency modulate.

Improved crosstalk or interference between channels is also obtained. This is due to the fact that only one increment of the modulation signal is transmitted at any one instant and nonlinearities in the transmission system do not introduce interchannel crosstalk products such as would be obtained in the frequency division method. Also, the flexibility of pulses will constitute certain advantages in the interchange of transmission constants. For example, bandwidth for signal to noise ratio, crosstalk for bandwidth, number of channels for signal to noise ratio and other combinations. This adaptability will allow a design directly suited to the specific application.

1.4 Wideband Pulse Time Modulation

All research and development work on multiple communication systems using pulse techniques has been in the line of narrow band modulation and time division multiplex.

Normally, each channel in a pulse multiplex system covers an audio spectrum of 300 to 3000 cycles per second. Since the modulating signal in each channel must be sampled at a rate at least twice the highest frequency to be transmitted this means that the pulse repetition frequency, PRF, will be at least 6,000 per second. Experiment and spectrum analysis has shown that a practical multiplying figure is approximately 2.6 times the upper band pass frequency. This results in a PRF of 7,800 cycles per second and most equipments now being used round this off to 8,000 cycles per second. In terms of time this means that one bit of information will be transmitted every 125 microseconds. To multiplex ten channels it is necessary to have a PRF of 10 times 8,000 or 80,000 cycles per second and one bit of information will be transmitted every 12.5 microseconds. Actually only nine channels could be accommodated because the initial pulse of each frame must be a syncronizing or reference pulse for demodulation purposes. It should be noted that this discussion applies only to a system using asymmetrical PTM as the modulating principle.

A departure from this normal multiplex method was suggested by Mr. A. M. Levine of the Federal Telecommunication Laboratories. His idea was to use a multichannel carrier, having its intelligence channels separated on a frequency basis, as the modulating signal for a PTM system. Since the modulating signal would of necessity cover a large band

of frequencies the PTM generator must also be capable of wideband operation. A wideband PTM system of this type would enable the older AM equipments, multiplexed by frequency division, to utilize the advantages of the newer pulse techniques for transmission purposes. Such a device would have considerable commercial and military application.

The particular system described in this paper was designed to be used with an existing equipment whose output was a multichannel frequency divided signal with a bandwidth of 0.3 to 60 KC. Since the multiplexing had been accomplished ahead of the PTM generator it was only necessary to provide a single channel wideband PTM modulator and demodulator.

CHAPTER II

GENERAL CONSIDERATIONS

2.1 Overall System

This system was designed and constructed with the idea of demonstrating the feasibility of wideband PTM. Since it was to be only a laboratory model and not a commercial finished equipment many shortcuts and assumptions could be made. These engineering liberties will be mentioned and explained at each point in the circuit where they apply.

There were four specifications that had to be taken into consideration during the design of the overall circuit. These were: the non-linear distortion had to be in the order of 60 db down, output pulse of the modulator to have a 0.5 microsecond duration, very few or no "active" circuits to be employed and, if possible, no synchronizing pulses to be transmitted.

The first of these is fairly obvious if you will recall the type of modulating signal used. Any non-linear distortion in the pulse system will introduce intermodulation between the sub channels of the input signal and result in crosstalk between channels. The requirement of 60 db down or 0.1% distortion is perhaps a bit severe but should be obtainable with proper design and careful construction.

The decision to have the output pulse of 0.5 microsecond duration comes directly from the fact that the majority of the rf equipment developed at Federal for pulse work operates on a half microsecond pulse.

The third specification is a trifle unusual and the answer lies not in theoretical circuit analysis but in practical design considerations. Engineers at Federal have found through use and experimentation that "active" circuits such as multivibrators, blocking oscillators electron-coupled oscillators and gas-tube relaxation oscillators are not as dependable on a long time basis as passive circuits. Passive circuits being defined as those that only shape the waveform rather than generate directly the type of pulse desired. This specification was not difficult to obtain but it did weigh heavily in the overall circuit design.

The last circuit requirement, that the receiver be able to operate properly with no synchronizing pulse being transmitted, was the most interesting problem to be solved. The logic behind this requirement was to reduce the overall circuit complexity. Simplicity and reliability being two qualities that were desirable in the finished design.

The modulator and demodulator use for the most part standard tested circuits, but operated far in excess of their usual repetition rates. There was little or no information on these circuits being used at high rates, so the design, or perhaps it should be said redesign, was in part computation and in part experimentation. In the majority of cases the computed values merely located the area to start experimentation. The principal difficulty was a lack of practical design and construction work in

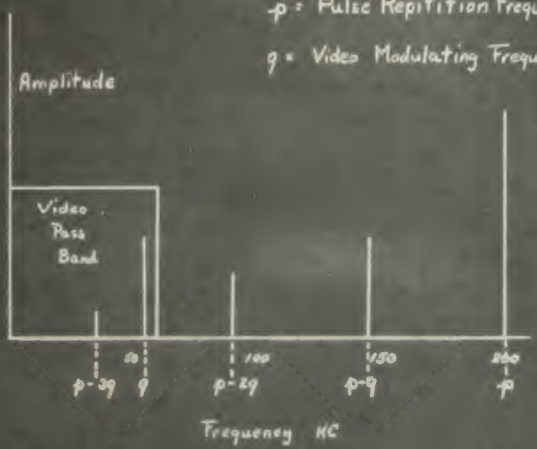
this frequency range so that assumptions or estimations of distributed capacitance was in most cases entirely erroneous. This is practically a fatal error when working with pulses of short duration since the rise and decay time is a function of the high frequency response which in turn is dependent on distributed capacitance.

The sampling rate for a system of this type, demanding a very low overall distortion figure, is not only dependent on the method of demodulation but also on a spectrum analysis of the modulated pulse train. Spectrum analyses for various modulation types have appeared in the literature and text books, but to date no one has succeeded in obtaining a closed relation for asymmetrical PTM in terms of the modulating frequency, repetition rate and circuit parameters. However, it has been pointed out by E. R. Kretzmer (6) that if the demodulation process in part consists of generating asymmetrical PWM pulses, one edge being formed by the synchronizing pulse, and the other by the information carrying pulse, then an analysis of PWM is required rather than PTM.

There are three standard methods used to demodulate PTM. One is as mentioned in the previous paragraph; another uses a discriminator; the third utilizes either a single or double coincidence type of circuit. The discriminator circuit was automatically discarded because of the large bandwidth involved. The coincidence system was rejected because of its

complexity and lack of experimental data on performance. Since it was decided to reconvert to PWM the facts and figures used in the article mentioned above were used as a basis to decide the PRF to be employed.

Some of the salient points of the article as apply to PWM can be mentioned here: The spectrum of the d-c-pulses, in the absence of modulation, consists of lines at the pulse repetition frequency p and its harmonics np. Modulation by a sinusoid of frequency q produces additional spectral lines, one at frequency q which represents the useful signal component, and an infinite set at frequencies $np \pm mq$ with m any integer and n any integer except zero. So-called intermodulation distortion results because some of these components fall into the audio band, or video band in this case, and cannot be seperated from the useful or desired components, as shown in figure 4. The only components apt to be significant are those of frequencies $p - q$, $p - 2q$ and $p - 3q$. The former is of the same magnitude as the useful signal component of frequency q and is in fact an exact inversion of this; it occurs in any periodic sampling process and the necessity for its exclusion from the pass band is responsible for the basic rule that the sampling frequency must exceed twice the highest signal frequency in order to make faithful reproduction possible. The latter components, at frequencies $p - 2q$ and $p - 3q$, range from a fraction of one per cent of the desired component in the case of symmetrical PWM, through



Video Spectrum of PWM

Figure 4

several percent for low-index asymmetrical PWM such as is obtained in most present day PTM systems, to about thirty percent for the $p - 2q$ component in the case of high-index PWM which is possible only on single-channel applications such as this is to be. Therefore, for this application it will be necessary to exclude the $p - 2q$ component, which will call for a PRF more than three times the highest modulating frequency. The intermodulation distortion, however, is generally much less severe than indicated by the above figures, because the spectral components in question fall into the video band only when caused by relatively high values of the signal frequency q, where the signal magnitude is relatively small; this makes the index of modulation effectively smaller as far as the undesired components are concerned, and the magnitude decreases rapidly with decreasing index.

Bearing these facts in mind the pulse repetition frequency of the system was set at 200 KC.

2.2 Modulator

The modulation process used in this design corresponds to standard techniques in all respects except one. A master oscillator is used to generate a timing waveform; this timing wave and the video modulating signal are combined to form asymmetrically duration-modulated pulses; finally the modulated edges of the PWM are used to produce time-modulated half microsecond pulses. Notice that only the modulated pulses were retained. Since there is to be no synchronizing

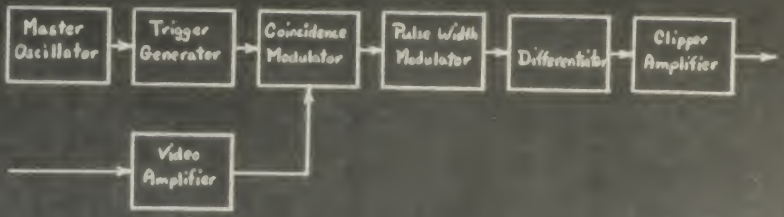
signal transmitted, the pulse corresponding to the unmodulated edge of the PWM was discarded.

The PWM generator is the only radical departure from convention methods employed in pulse time modulation. Normal procedure is to use some form of the voltage saw-tooth method of pulse width modulation in which the basic process is amplitude selection of a portion of a triangular waveform. There are numerous variations of this method but all of them mark the instant of equality of two voltages and use some property of a nonlinear circuit element as their fundamental operating characteristic. A few of the more common devices of this type are: the nonlinear characteristic of the ideal diode, the "broken-line" characteristic exhibited at the cut-off point of many thermionic tubes and contact rectifiers and the well known blocking oscillator characteristics. The principal disadvantage of this system when applied to the problem at hand was that the time available between samples was insufficient for circuit recovery. A PRF of 200 KC means that each sample must be generated and the circuit recovered in 5 microseconds. Using the sawtooth method of generation meant that the timing wave generated must have a linear rise of 4 microseconds and a decay time of 1 microsecond. An experimental sawtooth generator was constructed and an attempt made to operate it at the rates desired. It was found that it was impossible to obtain the recovery times necessary. The difficulty encountered was trying to reduce

the RC of the discharge circuit. This value was a function of the switch tube's r_p, which of course could not be varied, and the capacitance in the sawtooth generator. Reducing the capacitive value to less than 10 micromicrofarads did not even approach the time of discharge wanted so this method was abandoned. If further information is desired on the subject of voltage sawtooth methods of pulse width modulation the reader is referred to volume 19 of the Radiation Laboratory Series by Britton Chance. (1)

The PWM generator finally used was a circuit suggested by Mr. R. R. Waer of the Federal Telecommunication Laboratories. This method used a pentode coincidence tube with the video modulating signal placed on the grid and a sharp positive pulse derived from the master oscillator applied to the suppressor. A negative triangular waveform is generated in the plate circuit with the amplitude of the sharp leading edge proportional to the instantaneous grid signal and the width of the base a function of the charge RC. The integrating effect of a finite sampling time can be assumed to have negligible effect on the circuit distortion since the sampling time is negligible compared to the period of the applied video signal.

Figure 5, a block diagram of the completed wideband PTM modulator, shows the modulating signal input as coming from a video amplifier. One of the engineering liberties mentioned previously was taken here. This amplifier would be necessary



Wideband PTM Modulator

Figure 5

on a commercial model to match the output of the multiplex terminal equipment. In the laboratory set-up constructed, this item was simulated by a signal generator connected directly to the circuit.

The master oscillator had the requirement of being simple, reliable and fairly stable on a long time basis. Extreme stability such as is associated with a crystal controlled unit was not necessary since the type of synchronizing used in the demodulator should be able to follow any slowly varying frequency drift. An unusual design known as the Butler oscillator circuit appeared to fulfill all the necessary requirements and was used in this portion of the equipment.

The trigger generator used to provide the sampling pulse for the coincidence modulator is entirely conventional. An LC peaker in the plate of the first tube produces a sharp positive pulse of energy when the tube is cut off. A diode shunted across the LC tank effectively damps out any oscillations following the first positive cycle. Two pentode amplifiers then bring the trigger pulse up to the amplitude necessary for driving the coincidence modulator.

Considerable difficulty was experienced in clamping the base of the triangular waveform appearing at the plate of the coincidence modulator. Neither crystals or diodes would remove the slight bit of modulation that was encountered. A satisfactory solution was finally obtained by

using a triode in the manner shown on the circuit diagram, figure 11, page 36.

The remainder of the modulator was entirely standard. A quasi-differentiating circuit produced PWm from the triangular waveform, a standard differentiator generated pulses and a series of three pentodes shaped and amplified the modulated pulses.

Another liberty was taken at this point in the design. Normally this modulated pulse would be used to drive a transmitter and some type of matching device would be necessary from the output of the modulator to the input of the transmitter. However, in the experimental model it was assumed that the pulses could be transmitted, received and rebuilt to be identical with the modulator output. Due to this assumption, the output stage is a voltage amplifier instead of a power amplifer and is fed directly into the demodulator.

2.3 Demodulator

The demodulator design presented two very interesting problems. The first of these, as was mentioned previously, was the matter of keeping the demodulator in synchronization with the modulator although no synchronizing pulses were to be transmitted. It was felt that since this was to be a single channel system the essential PRF information was contained in the long time average position of the modulated pulses.

A somewhat similar problem had faced the television manufacturers in the design of their horizontal synchronizing circuits so a study was made of these devices. With this background a satisfactory locking oscillator was developed for the frequencies concerned and applied to the synchronization of the demodulator.

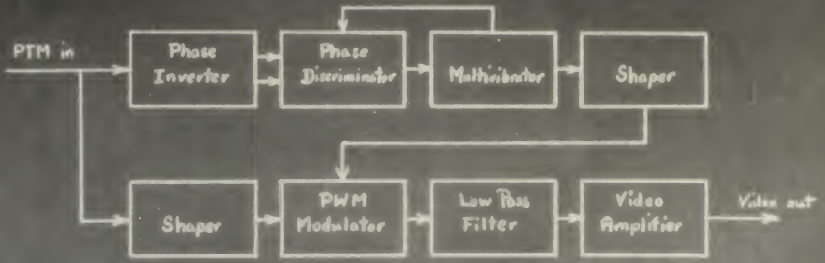
The second problem was to regenerate PWM from the two signals available; the timing output of the locked oscillator and the incoming PTM. It should be simple, reliable and contain no active circuits of the multivibrator type. The higher PRF used in the wideband system created a different situation than that found in commercial PTM equipments. A large portion of existing PTM demodulators used a one-shot multivibrator to convert to PWM. The timing wave being used to form the fixed leading edge and the modulated pulse the variable trailing edge. However, the overall distortion problem is reduced considerably at the lower PRFs and this type circuit can be tolerated.

The characteristics of the 6AS6 coincidence tube, which had been studied in connection with the coincidence modulator, suggested that successful conversion could be accomplished in one tube with proper shaping of the input signals. The waveforms applied to V_{15}, the PWM generator, as shown in figure 14, page 42, were the signals finally developed to convert to PWM. Fortunately the time relationship between the two waveforms was taken care of by the inherent circuit

delay of the locked oscillator and following pulse shaper.

Recovery of the original video signal was done by means of a low pass filter in the conventional manner. An attempt was made to use a sharp cutoff filter designed to operate at 60 KC, but difficulty was encountered due to the filter ringing when a square pulse was applied. This trouble was overcome by applying the PWM pulse train first to a Gaussian filter, one whose cutoff characteristic follows a Gaussian distribution curve, and then to the sharp cutoff circuit.

A block diagram of the demodulator for the wideband PTM system is shown in figure 6.



Wideband PTM Demodulator

Figure 6

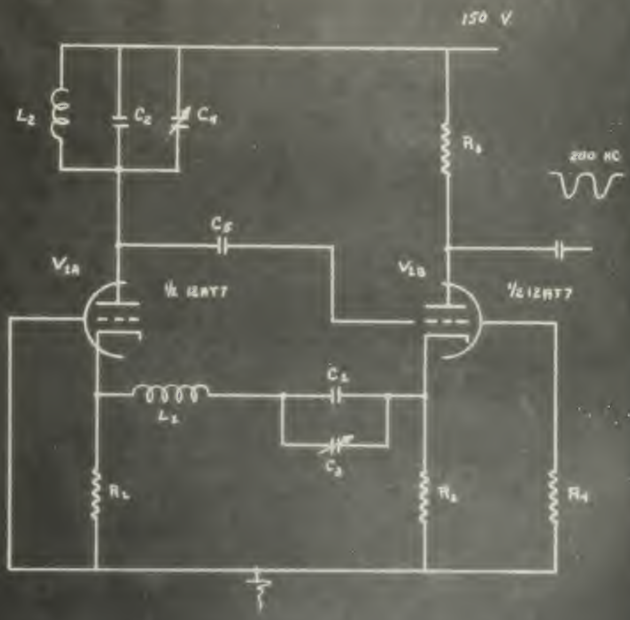
CHAPTER III

MODULATOR CIRCUIT DETAILS

3.1 Oscillator

A schematic of the Butler oscillator is shown in figure 7. The primary frequency determining element is the series resonant circuit, L1C1, placed between the two cathodes. Since the PRF was to be 200 KC this resonant circuit was tuned to the above figure. A one millihenery coil was used for the inductance mainly because of the availability. This selection determined C which was computed to be approximately 650 micromicrofarads. A small variable capacitor, C3, with a maximum capacitance of 50 micromicrofarads, was used in parallel with a mica 600 micromicrofarad capacitor so that some measure of control could be exercised. This arrangement resulted in approximately a 10 percent control of the oscillator frequency.

The parallel tuned circuit in the plate of V1a is actually not needed in this application and could be replaced with a load resistance. It was originally planned to use a 200 KC crystal operating in its series resonance mode as the controlling element. The tuned circuit in the plate would then be used to prevent the crystal from operating in any of its spurious modes. However, since the demodulator was designed to function with a locked-in oscillator the stability of a crystal was not necessary.



Master Oscillator

Figure 7

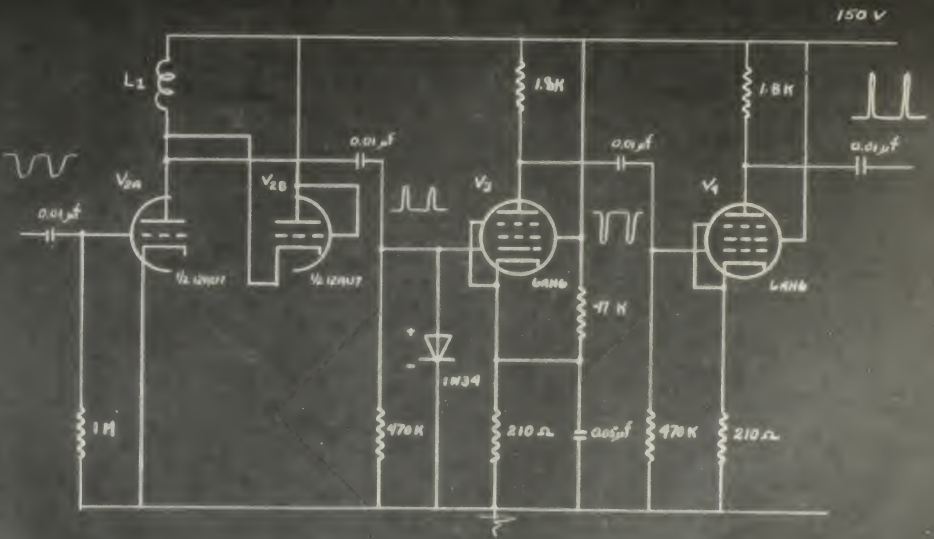
The breadboard had already been started by the time it was determined that a crystal could be eliminated and the plate tank circuit was retained as an additional means of control. L2 and C4 are identical with L1 and C3. It was found that C2 had to be 670 micromicrofarads rather than 600 in order to maintain proper center frequency. The variation in capacitance can probably be explained by additional shunting and wiring capacitance being present in the cathode circuit and a difference in distributed capacitance between the two coils.

The R4C5 combination in the grid circuit of V1b controls the amount of feedback and consequently the output wave shape. It was desired to have a negative pulse to drive the following stage to cutoff so this combination was selected to give a negative pulsed output. These values were not computed but arrived at by experimentation, and were found to be 0.01 microfarads and 100K.

The cathode resistors and the plate load of V1b were chosen to place the tube, a 12AT7, in a linear operating region of its curves. The 12AT7 was selected primarily for its amplification factor since the following stage required a high voltage driving signal. R1 and R2 were both 560 ohms and R3 was 10K.

3.2 Trigger Generator

The negative pulsed output of the master oscillator is applied to the trigger generator shown in figure 8 and shaped



Trigger Generator

Figure 8

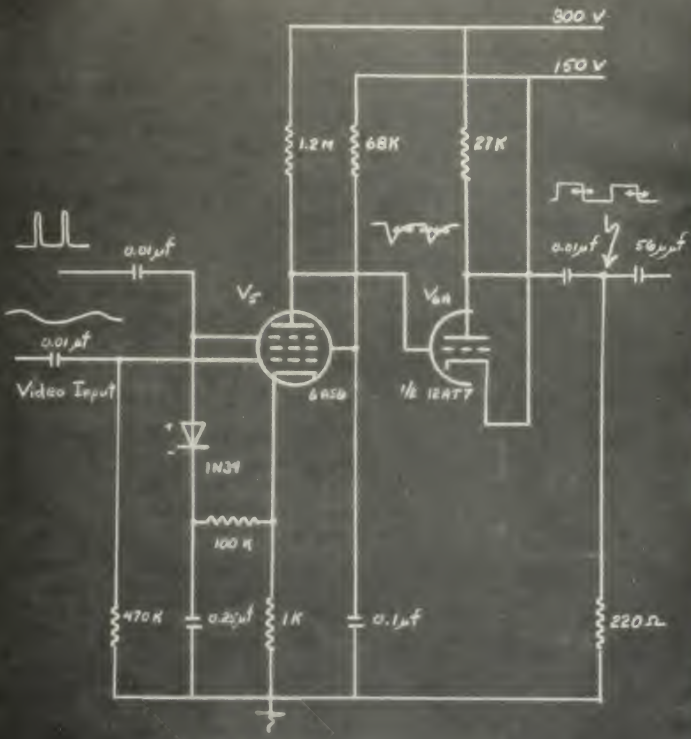
into a narrow positive pulse occurring at the PRF. These pulses are approximately 0.2 microseconds wide and of sufficient amplitude to drive the coincidence modulator.

The plate load of the first tube, V2a, is simply a coil, L1, shunted by V2b connected as a diode. This can actually be considered as a "ringing circuit" with the capacitance being composed of the distributed capacitance of the coil plus any wiring and tube capacitances present. The diode acts as a damping resistance and removes all oscillations after the first positive half cycle. Since the voltage necessary for cutoff is considerably higher during the positive swing than that normal for the Ebb shown the input driving signal must have a large negative voltage swing.

The output of the pulse generator is then applied to two pentodes where it is clipped and amplified to provide the input to the next stage. The design of the pentode amplifiers follow the relations and rules of thumb developed in Appendix A. Since the appendix is self-explanatory and will show the reasoning behind some of the unusual component values, nothing further will be said at this point concerning pulse amplifiers.

3.3 Coincidence and Pulse Width Modulator

V5, the coincidence modulator, is activated for approximately 0.2 microseconds by the positive pulse from the trigger generator. During this period the voltage drop in the plate will be proportional to the value of the signal on the grid. Since the grid input is the video modulating signal this plate



Coincidence and Pulse Width Modulator

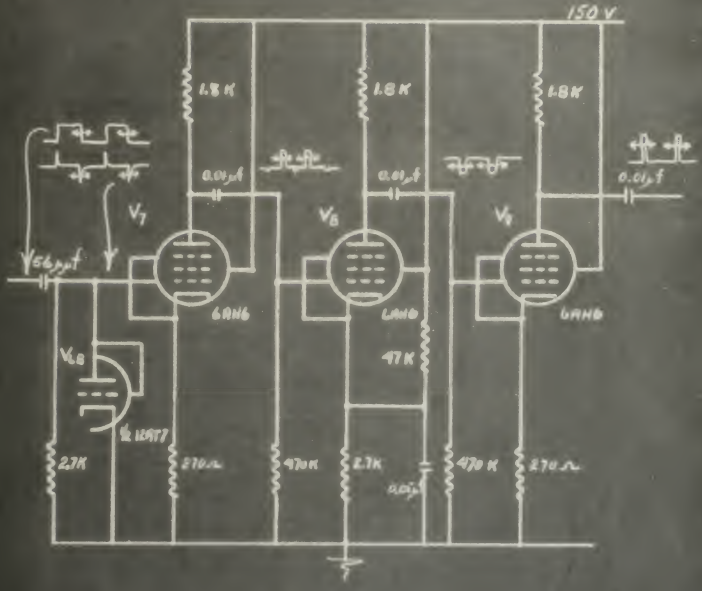
Figure 9

voltage drop can be considered as one form of pulse amplitude modulation. When V5 is cutoff the plate relaxes toward a value determined by the triode, V6a. This value is approximately 150 volts due to the fact that in the quiescent state V6a is drawing grid current. The charge to 150 volts occurs in a time determined by the amount of plate drop and the charge RC constant. This results in a negative triangular waveform clamped at 150 volts and whose amplitude and base width is proportional to the applied grid signal. This waveform is shown in figure 12, page 37. It was found by experimentation that some type of reference between suppressor and cathode must be provided in order to maintain the dc level of grid 3 below cutoff between pulses. The solution was found to be the 1N34 crystal and 100K resistor shown in figure 9.

The coupling capacitor and 220 ohm resistor to ground form a differentiating circuit so that the waveform at the junction between the two capacitors shown in figure 9 is PWM with a fixed leading edge and modulated training edge.

3.4 Differentiator and Pulse Amplifiers

Very little need be said about this portion of the circuit. A standard RC differentiator transformed the PWM into positive and negative pulses and the following pulse amplifiers clipped and amplified to obtain the PTM desired. The design of these amplifiers is again taken care of in Appendix A. The reader is again reminded that liberties

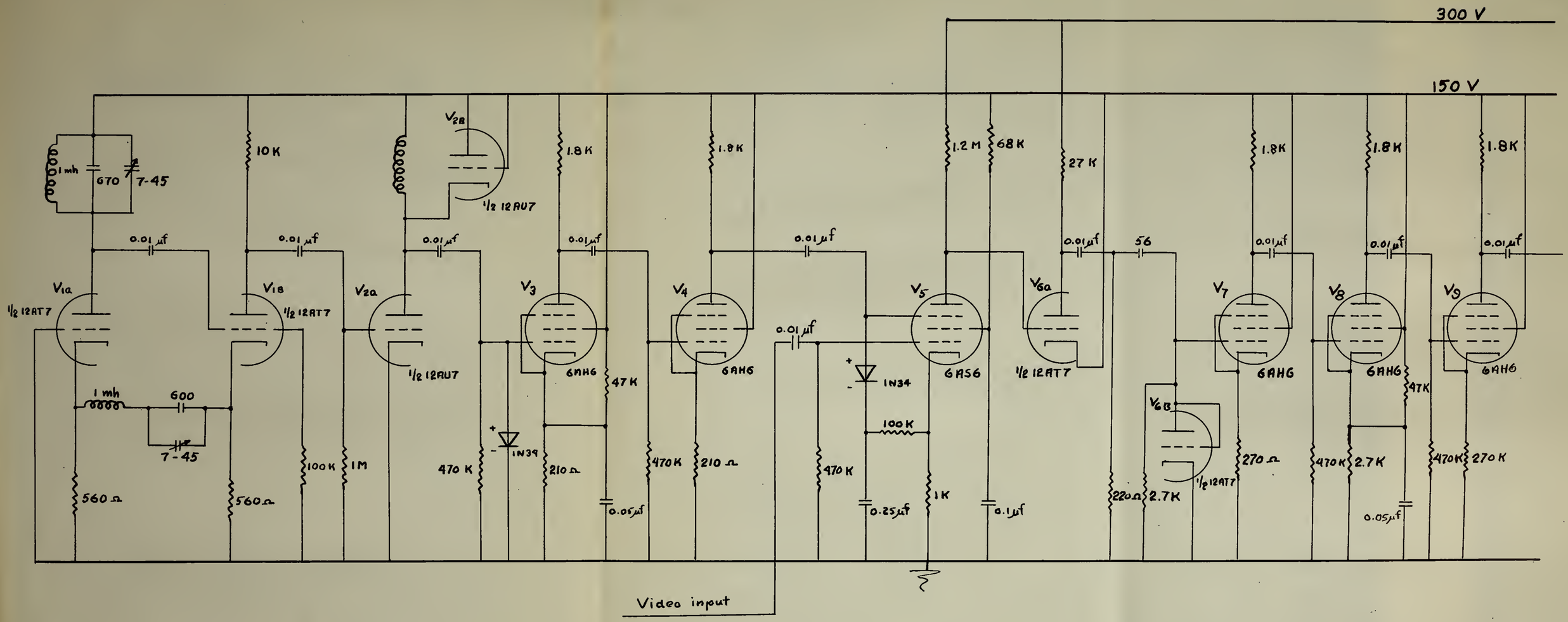


Differentiator and Pulse Amplifiers

Figure 10

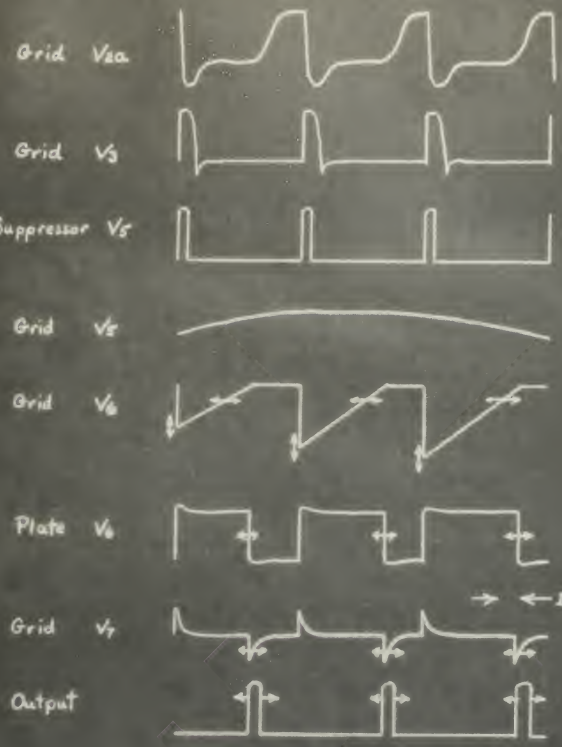
were taken at this point in that the last stage is not a power stage nor an impedance matching device. Actually the last stage in this circuit is used merely as a phase inverter.

A complete circuit diagram is shown in figure 11. Figure 12 is a series of waveforms taken at various points in the completed circuit. These waveforms are in their proper phase or time relationships.



WIDEBAND PTM MODULATOR

Figure 11



Modulator Waveforms

Figure 12

CHAPTER IV

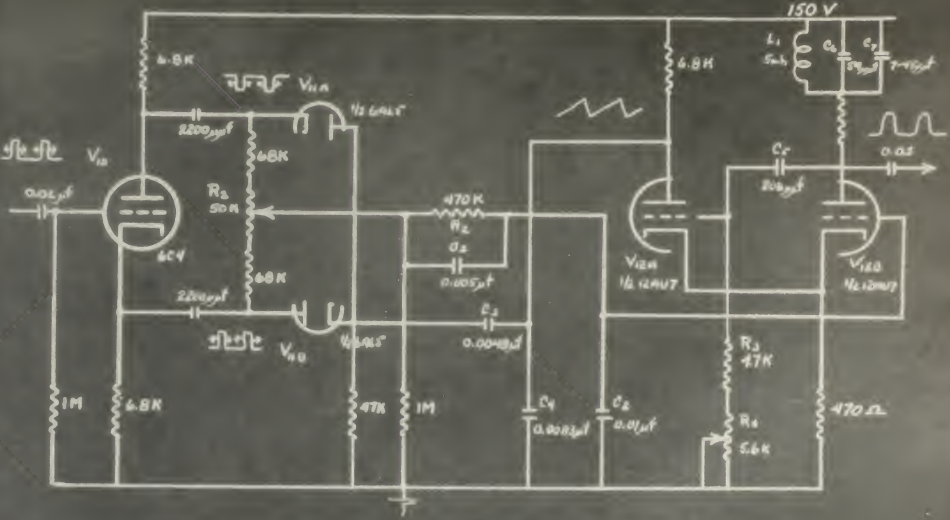
DEMODULATOR CIRCUIT DETAILS

4.1 Synchronization

The synchronizing device used in the demodulator is a so-called locked oscillator operating on the long time average position of the incoming PTM. As shown in figure 6, page 26, it is composed of three individual circuits; a phase inverter, phase discriminator and a controlled multivibrator. This multivibrator incidently is the only "active" circuit used in the entire system. A feedback loop from the discriminator to the multivibrator provides the control necessary to obtain proper operation.

V12a and V12b together with associated circuitry shown in figure 13 comprise a free running multivibrator. Essentially there are three methods of control used on this circuit; the RC combination in the grid of V12a, the tank circuit in the plate of V12b and the dc level at the grid of V12b. Primarily the frequency is a function of R3, R4, and C5. The parallel resonant circuit in the plate is used to shape the output into a sinusoidal waveform. The feedback to the phase discriminator is taken off the plate of V12a and is a sawtooth shaped wave.

The incoming PTM is applied to the phase inverter V10 and the two resulting signals used to drive the phase discriminator. The peak to peak amplitude of the pulses on the plate of V11b and the cathode of V11a was approximately 14 volts.



Locking Oscillator

Figure 13

The combination of the two waveforms applied to the phase discriminator results in a slowly varying plus and minus voltage across R1. The pulses are in effect riding up and down on the negative going portion of the sawtooth and the voltage appearing across R1 is a function of the phase of the two signals. It was found by experimentation that the amplitude of the sawtooth voltage should be approximately two thirds the amplitude of the phase inverter output. The peak to peak value of the sawtooth was adjusted to 10 volts by means of the capacitive divider C3 and C4. The slowly varying output of the phase discriminator is picked off from the balance control, R1, smoothed in a filter, R2, C1 and C2, and used to set the dc level of the multivibrator grid.

Initally the free running rate of the multivibrator was adjusted to within 5 percent of the modulator PRF with the tank circuit shorted out and R4 approximately centered. The short was then removed and the output again adjusted to the same frequency by tuning the parallel resonant circuit. With an applied PTM signal, final adjustments could be made with R4 until lock-in was accomplished. In practice this circuit would lock on and hold with over a 5 percent variation in the modulator PRF.

4.2 Pulse Width Generator

The next logical circuits to discuss in the sequence of operations would be the shapers used to generate the proper

signals to be applied to the pulse width generator. However, in order to properly understand the need for the derived waveforms, it is necessary to first investigate the manner by which the PWM is developed. Basically it is an overlap type of device using the two shaped signals to drive a 6AS6 coincidence tube. The pertinent waveforms are shown in figure 14.

"A" is simply a marker indicating the PRF of the modulator. "B" shows four pulses of the incoming PTM. Pulse number 2, since its leading edge corresponds to one of the PRF markers, will be considered as unmodulated. Correspondingly then, pulse number 1 represents a maximum negative modulation and number 3 a maximum positive swing. This plus or minus 0.5 microsecond deviation from an unmodulated position is known as the depth of modulation and for this application is 20%. That is, the total swing plus and minus is 1 microsecond or 20% of the 5 microsecond pulse repetition rate. The first three pulses represent a sequence that would be impossible to duplicate in the equipment. They are presented in this manner simply to illustrate the limitations of an overlap system at the extremes of modulation. "C" is a 2.5 microsecond square wave generated from the timing wave output of the locked oscillator. Waveform "D" is the shaped signal generated from the incoming PTM. The numbers 1, 2 and 3 correspond to pulses 1, 2 and 3 in "B". The output of this coincidence circuit is PWM as shown in "E". The PWM pulses are marked 1a, 2b and 3c corresponding to a combination of the

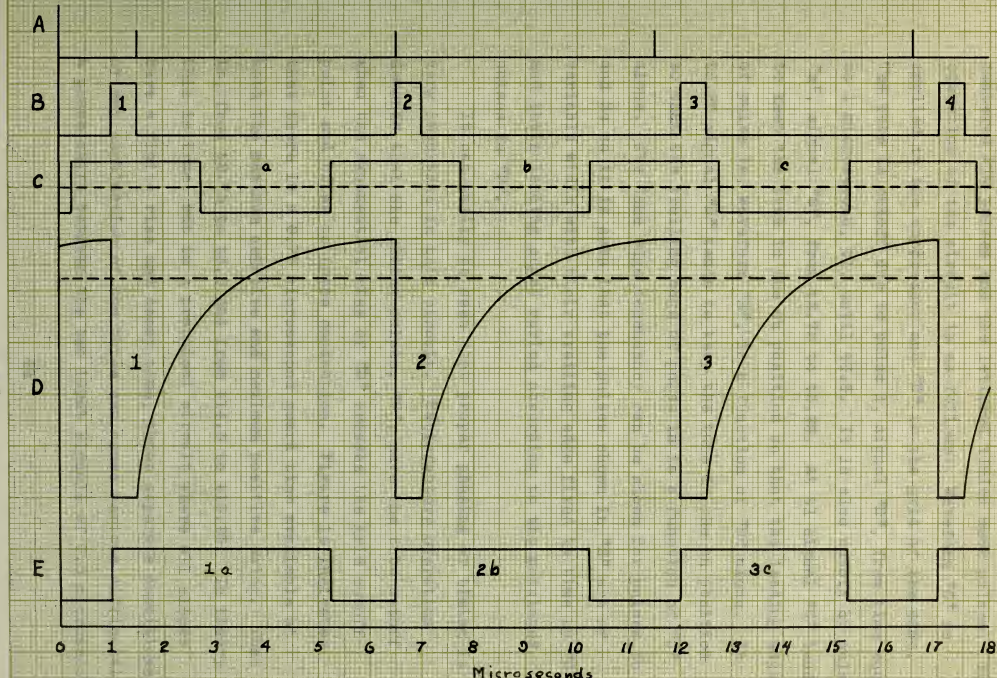

A
B
1
2
3
4
C
a
b
c
D
1
2
3
E
1a
2b
3c
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18
Microseconds

Figure 14

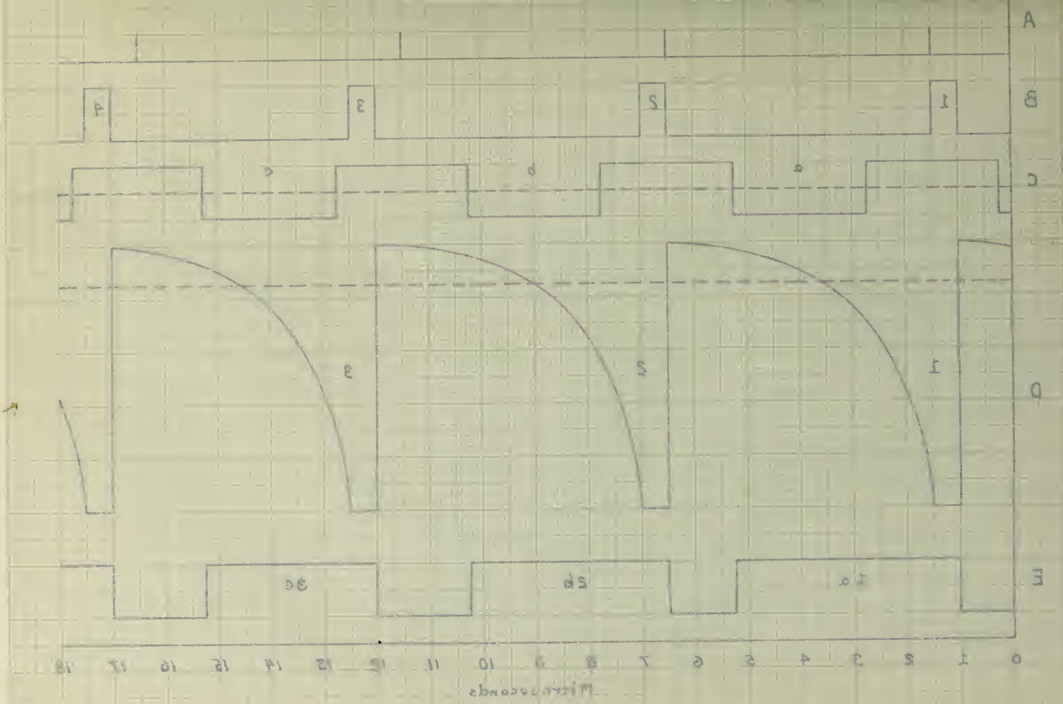

A
B
C
D
E
1
2
3
4
a
b
c
1
2
3
1a
2b
3c
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18
Microseconds

Figure 14

numbered PTM pulses and the lettered timing wave pulses. The operation of the circuit is as follows: Waveform "C" is applied to the suppressor and "D" to the grid of the 6AS6. The tube is cutoff due to pulse 1, signal "D", from time equal to 1 microsecond, t1, until t3.5. It is also cutoff by pulse "a", signal "C", from t2.75 to t5.25. At t1 signal "C" tends to keep the tube in the on position so that the leading edge of pulse 1a, waveform "E", is a function of "D" alone. At t5.25 signal "D" tends to keep the tube in the on position so that the trailing edge of pulse 1a is a function of "C" alone. The same edge dependancy can be shown for pulses 2b and 3c so it is seen that the pulses shown in "E" are of variable width with their trailing edge fixed in time by "C" and their leading edges varied according to the modulated pulses in "B".

It can easily be seen that proper phasing or timing is very important in this circuit. Satisfactory operation demands that the timing pulses, "C", have the tube cutoff when the exponential rise of "D" crosses the grid cutoff point and tries to force conduction. Figure 14 indicates that there is a 0.75 microsecond guard time available at both the maximum negative and maximum positive swing. That is, from t2.75 to t3.5 and from t14.5 to t15.25. In theory this is true, but in a practical circuit where all slopes have a finite rise and decay time, three seperate conditions or any combination of the three can cause serious difficulties. A phase shift between the two input signals of 0.5 microseconds

can result in poor edge definition of the PWM since less than 0.25 microseconds seperate two conflicting controls. A change of approximately 12 percent in the value of the charge RC time constant will shift the cutoff point well over 0.5 microseconds and the same conditions as before will prevail. Variation in the amplitude of "D" due to changing tube parameters, plate voltage or input signal strength will also move the point of cutoff although not as rapidly as the first two mentioned. A fourth condition that could occur is an increase in the depth of modulation. This, however, should be controlled at the modulator and is not properly a fault to consider in the demodulator.

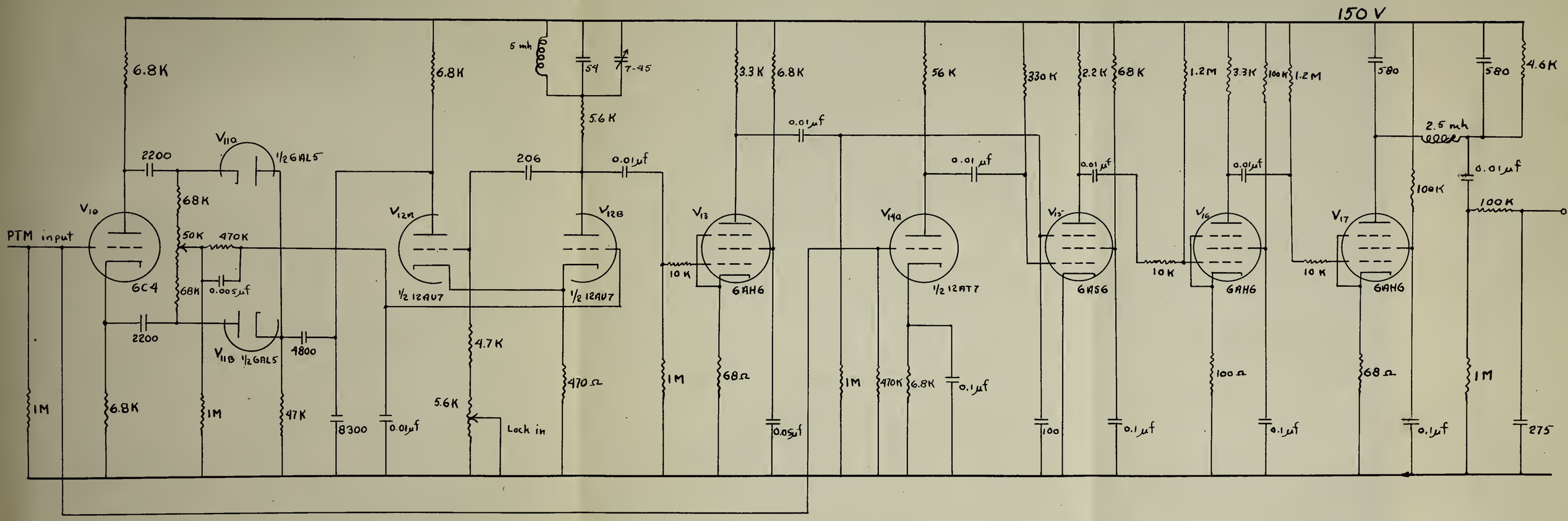
The breadboard that was constructed suffered at one time or another from all three conditions mentioned. It was found that the most effective method of adjustment, after obvious waveform corrections, was to decrease the depth of modulation at the modulator until the proper PWM output was obtained at the plate of the 6AS6. Later experimentation showed that if the phasing was closely controlled then a variation of the charge RC or a change in amplitude of the grid signal did not present to much of a problem. The slight overlap of two conflicting functions, such as "C" and "D" at t2.75, due to a change in circuit constants would result in a small pulse at the point in question, but its amplitude was of such a value that proper biasing and clipping in the following stages would remove the error.

4.3 Demodulation

The output of the PWM generator is used to drive two pentode pulse amplifiers. This brings the signal up to an amplitude sufficient for demodulation. The original video signal is recovered from the PWM by the conventional means of a low pass filter arrangement. The filter in the plate circuit of V17, figure 15, is a so-called Gaussian filter. It receives its name by virtue of the fact that the response characteristics at the frequency of cutoff follow a Gaussian distribution rather than a sharp cutoff. As mentioned in Chapter II, a sharp cutoff filter has a tendency to ring when a pulse with sharp leading and trailing edges is impressed on it. The Gaussian filter incorporated performs the function of removing a good share of the high frequencies without ringing and presents what is essentially a triangular waveform to the following sharp cutoff filter. This final filter removes the remainder of the high frequency components above 60 KC and the original video modulating signal appears as its output.

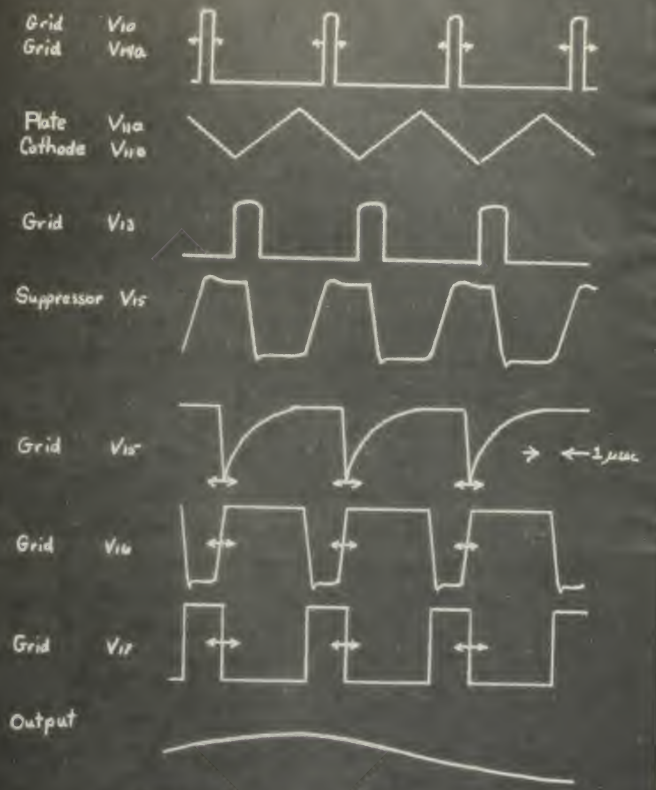
The output stage of the demodulator is another place where engineering liberties were taken. Normally a power stage followed by a matching device or impedance transformer would be used. For purposes of demonstration, the output of the filter was applied directly to an oscilloscope.

A complete circuit diagram is shown in figure 15. Figure 16 is a series of waveforms taken at various points in the completed circuit. These waveforms are in their proper phase or time relationships.



WIDEBAND PTM DEMODULATOR

Figure 15



PTM Demodulator Waveforms

Figure 16

CHAPTER V

POSSIBLE MODIFICATIONS

5.1 General

One source of distortion in the overall system is a rather obvious consideration that was neglected in the preliminary design. Decoupling was not incorporated at any point in the circuit. The reason for this omission is twofold; first of all it is impossible to determine theoretically which stages will require isolation, second, it was on the advice of a project engineer to construct without decoupling, determine the offending circuits and then decouple. Suggestions for these modifications appear in the following two divisions of this chapter.

Another general improvement would be to raise the working voltage of most stages from 150 volts to 300 volts. This would probably eliminate several tubes that were used more for circuit gain than for shaping.

5.2 Modulator

It was pointed out in Chapters II and III that a coincidence method of modulation results in time modulation proportional tothe integrated value of the grid signal during the time of sampling rather than the instantaneous grid value. If a narrower trigger pulse were used, the linearity of the overall system would be improved since the output pulse would more nearly approach a value of time displacement that is exact.

Observations at various points in the completed circuit indicate that the decouplung necessary can be accomplished by isolating the following combinations of tubes: V1a and V1b. V2a, V2b, V3 and V4. V5 and V6a. V7, V8, and V9.

5.3 Demodulator

Chapter IV stressed the importance of proper phase relationships for the correct operation of the pulse width modulator. It was originally intended that the phasing be controlled by means of a delay line following the timing pulse generator. The value of the delay necessary to be determined experimentally. This portion of the circuit was omitted when it was found that the inherent circuit delay of the locked oscillator was approximately correct, and that the lock-in control, R4, could adjust the phasing over a small area. However, the difficulties encountered indicate that a more positive method of phase control is needed. Since the output of the locked oscillator can be made essentially sinusoidal a RC phase shifting network would seem to provide the simplest method of adjustment.

The low pass filter design is somewhat inadequate and does not perform its function in the manner desired. It is sufficient for the qualitative results wanted in this particular project, but a better design will be necessary for the quanitative measurements to be made on the second model. The subject of filtering was not studied sufficiently for any valid suggestions to be made at this point other than

an improvement is necessary.

Decoupling is recommended for the following combinations of tubes: V10, V11a, V11b, V12a and V12b. V13. V14. V15. V16 and V17.

CHAPTER VI

CONCLUSIONS

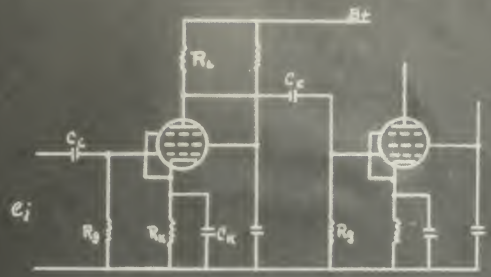
The equipment as designed and constructed fulfilled three of the four requirements enumerated in Chapter II. The modulator output was a 0.5 microsecond pulse capable of being time modulated over a 0.3 to 60 KC bandwidth. The demodulator operated satisfactorily with no synchronizing pulses being transmitted and recovered the original video signal over the entire bandwidth desired. Finally, only one "active" circuit was employed in the entire design.

The one specification not satisfied was the system non-linear distortion level. It was realized at the start of this project that the first design probably would not accomplish the 60 db level desired in the finished product, and that the first operating model obtained would, in general, only demonstrate the feasibility of wideband PTM. The suggested modifications should effectively reduce the amount of non-linearity present and approach the goal of 0.1 percent distortion.

The continued development of wideband PTM should produce a commercially acceptable equipment that will successfully bridge the gap between older methods of multiplexing and the newer means of pulse transmissions. Military and commercial application of this system will enable existing equipments to be utilized in the microwave regions. This will effectively decrease the amount of transmitted power needed, afford

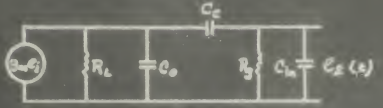
a greater measure of security, and, to a large degree, reduce the complexity of relay stations. This last advantage is due to the fact that frequency multiplexed signals must be demodulated, amplified and recombined at each repeater station. Pulse communication systems do not require this complexity at relay points.

In view of the advantages offered by this system, the relatively simple terminal equipment required and the ability to operate in conjunction with existing equipment, it is felt that the future of wideband PTM is assured.



RC Coupled Amplifier

Figure 17

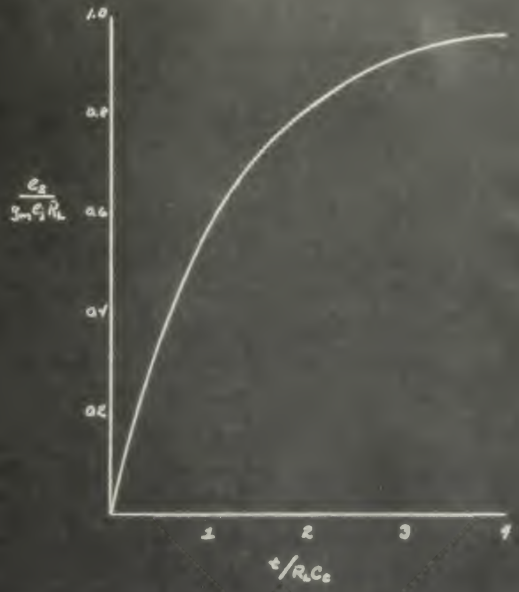


Equivalent Circuit of Fig. 17

Figure 18

Simplified Equivalent Circuit

Figure 19



Rise of Rectangular Pulse in RC Pulse Amplifier

Figure 20

voltage. The solution as a function of time is the well known exponential type which typifies the charging of a condenser through a resistor. It is shown analytically in equation (1) and graphically in figure 20. Thus if a rectangular pulse is applied to the amplifier, the output pulse will rise in accordance with the curves of figure 20 and decline along a similar path during the decay time.

$$e_2(t) = g_m e_i R1 (1 - e^{-t/R1Ct}) \qquad (1)$$

Equation (1) also shows that the amplifier gain is directly proportional to the load resistance, Rl. Therefore, it is desirable to make Rl as large as possible in order to obtain maximum gain. However, Rl is limited by the fact that the output voltage and gain reaches the maximum values when $t \gg R1Ct$. Hence for maximum fidelity of build-up time, the time constant R1Ct should be as low as possible. Since Ct is fixed by the tube parameters, this means that Rl should be as low as possible for the best pulse response. The value of load resistance used is usually a compromise between gain and pulse response, and is usually chosen to be the maximum value consistent with the required build-up and decay time characteristics.

A rule of thumb used by the engineers at Federal was that the output pulse edge would have approximately the same slope as the input edge if R1Ct is equal to one-quarter of the input pulse build-up time or time of rise. This relationship, as illustrated in equation (2), is a result

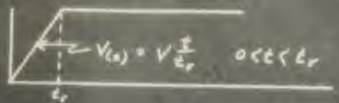
of analyzing the build-up time response of an RC circuit to a pulse with a finite build-up time or time of rise, tr.

$$RlCt = 0.25\ tr \tag{2}$$

To illustrate the analysis assume that the voltage waveform shown in figure 21 is applied to the simple RC circuit of figure 22. The output voltage between t equal 0 and t equal tr is:

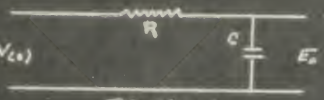
$$Eo = \frac{V}{tr}\left(t + RC\, e^{-t/RC} - RC\right) \tag{3}$$

A plot of this relationship is shown in figure 23.



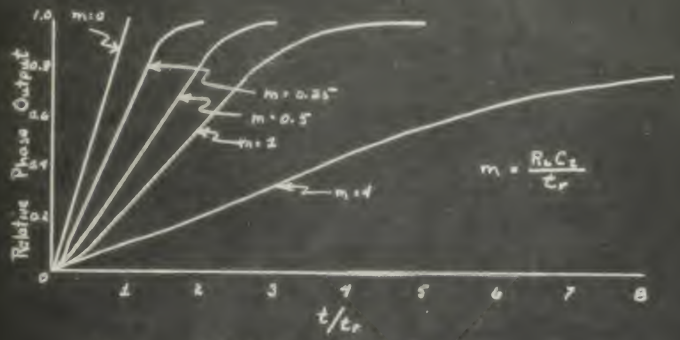
Applied Voltage

Figure 21



RC Circuit

Figure 22



Response of RC Pulse Amplifier to Pulse with Build-up Time t_r

Figure 23

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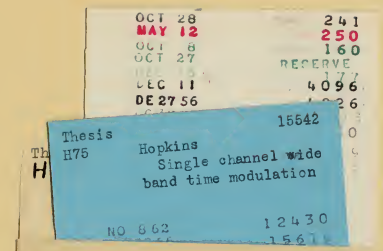
OCT 28
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DE 27 56
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250
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RESERVE
4096
Thesis
H75 Hopkins
Single channel wide
band time modulation
15542
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Wideband pulse time modulation.
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